Chapter 2

Quaternary Stratigraphy and Mapping in the Yucca Mountain Area

By John W. Whitney, Emily M. Taylor, and John R. Wesling[1]

Contents

Abstract

Stratigraphic studies and mapping of near-surface deposits, soils, and geomorphic surfaces provide essential data for determining the history of Quaternary faulting at Yucca Mountain. Eight surficial units, ranging in age from Pliocene(?) to Holocene, have been differentiated largely on the basis of relative stratigraphic and geomorphic position, lithology, soil-profile development, degree of desert-pavement development, amount and degree of desert-varnish accumulation, and degree of preservation of original bar-and-swale topography. Some deposits were dated by U-series analysis of pedogenic material and by thermoluminescence analysis of silt-size fractions of eolian and fluvial deposits. The presence of basaltic ash in fissure fills associated with fault zones aided in establishing the probable age of one of the major Quaternary surface-rupturing events; the ash is correlated with the eruption of the nearby Lathrop Wells volcanic center at 77±6 ka.

Deposits associated with geomorphic surfaces, including mostly alluvium and colluvium containing minor amounts of eolian and debris-flow deposits, make up the bulk of the surficial materials in the Yucca Mountain area. Descriptions of soil profiles and other distinguishing characteristics of the eight Quaternary map units were defined partly on the basis of natural exposures and partly on the basis of sequences exposed in trenches that were excavated to intersect and expose several of the major faults. The integration of stratigraphic, geomorphic, and numerical age data serves as a primary means for dating Quaternary fault activity at Yucca Mountain.

[1]Geomatrix Consultants, Inc., Oakland, Calif.

Introduction

Detailed studies and mapping of Quaternary stratigraphic sequences in the Yucca Mountain area (fig. 1) were conducted to determine the characteristics, relative ages, and distribution of the near-surface deposits, soils, and geomorphic surfaces that can be used to assess the history of Quaternary faulting in and near the proposed repository site for the storage of high-level radioactive wastes. An alluvial geomorphic surface (see Bull and Ku, 1975; Bull, 1991) is analogous to the top of an allostratigraphic unit, which is a mappable stratiform body defined and delineated on the basis of its bounding discontinuities (North American Commission on Stratigraphic Nomenclature, 1983). Primary characteristics used to date the map units include relative stratigraphic and geomorphic position, lithology, soil-profile development, degree of desert-pavement development, amount and degree of desert-varnish accumulation, and preservation of original bar-and-swale topography.

Surficial mapping of Quaternary deposits in the Yucca Mountain area has been progressively refined over the years (table 2). Early work in and near the Nevada Test Site (Yucca Mountain is at the west edge of the site) differentiated three

Table 2. Comparison of surficial deposits in the Yucca Mountain area, southwestern Nevada, with local and regional surficial stratigraphic sequences.

[Numbers in parentheses, ages in thousands of years]

Yucca Mountain (this report)	Yucca Wash, Nev. (Swadley and others, 1984; Taylor, 1986)	Crater Flat, Nev. (Peterson and others, 1995)	Kyle Canyon fan, Nev. (Reheis and others, 1992)	Fish Lake Valley, Nev.-Calif. (Harden and others, 1991; Slate, 1991)	East-central Mojave Desert, Calif. (Reheis and others, 1989; Wells and others, 1990)	Lower Colorado River, Calif.-Ariz. (Bull and Ku, 1975; Bull, 1991)
Qa7 (historical)	Q1b (0–15)	Modern (0)	Q4 (0)	Modern	Modern (0)	Q4b (0)
Qa6 (middle to late Holocene)	Q1b (0–15)	Crater Flat (<0.3–>1.3)	– – –	Late Marble Creek (0.1–1)	Q3b3 (0.5–2.5)	Q4a (0.1–2)
– – –	– – –	– – –	– – –	Middle Marble Creek (1–6)	Q3b2 (2.0–4.5)	Q3c (2–4)
– – –	– – –	– – –	– – –	Early Marble Creek (2–5.8)	– – –	Q3b (4–8)
Qa5 (latest Pleistocene to early Holocene)	Q1c (7–30)	Little Cones (>6–>11)	Q3 (15, 4–80)	Leidy Creek (6–11)	Q3b1 (6–11)	Q3a (8–12)
Qa4 (late Pleistocene)	Q2b (145–290)	Late Black Cone (>17–>30)	Q3 (15, 4–80)	Late Indian Creek (>50–<700)	Q3a (13–50)	Q2c (12–70)
Qa3 (middle? to late Pleistocene)	Q2c (270–440)	Early Black Cone (>159–>201)	Q2 (130, 18–750)	Early Indian Creek (>50–<700)	Q2b (110–130)	Q2b (70–200)
					Q2a (140–190)	– – –
Qa2 (middle Pleistocene)	QTa (900–2,000)	Yucca (>375)	– – –	Late Trail Canyon(?) (<700 [middle Pleistocene])	Q1b (>400–>650)	Q2a (400–730)
Qa1 (early to middle Pleistocene)	QTa (900–2,000)	Solitario (>433–>659 but <730)	Q1 (800, 750–800)	Early Trail Canyon (<700 [early Pleistocene])	Q1b (>400–>650)	Q2a (400–730)
QT0 (Pliocene? to early Pleistocene?)	– – –	– – –	– – –	– – –	Q1 (>650–>800)	Q1 (>1,200)

major upper Cenozoic stratigraphic units by using “correlation characteristics” (Hoover and Morrison, 1980; Hoover and others, 1981; Swadley and others, 1984; Hoover, 1989). The concept of correlation characteristics utilizes physical and morphologic features of landscape elements, including landforms, drainage network, soils (presence or absence of Av horizon), topographic position, desert pavement, desert varnish, depositional environment, and lithology. According to Swadley and others (1984), the oldest surficial deposits (unit QTa) in the Yucca Mountain area (fig. 1) are early Pleistocene and Pliocene(?), on the basis of an underlying deposit dated at about 2 Ma and an overlying deposit containing ash correlated with the Bishop ash, which was then dated at 740 ka but more recently at 760 ka (Sarna-Wojcicki, 1993). Units Q2 and Q1 of Swadley and others (1984) represent middle to upper Pleistocene and Holocene deposits, respectively (table 2). Each of the major geologic units of Hoover and others (1981) is divided into several subunits. A total of 10 subunits of units Q1 and Q2 and, possibly, 3 additional subunits of uncertain age that may belong to unit Q2 (Hoover and others, 1981) have been mapped in and near the Nevada Test Site. Swadley and others (1984) mapped the major upper Cenozoic stratigraphic units in Midway Valley, which adjoins Yucca Mountain to the east (fig. 2), but no detailed surficial geologic mapping that subdivided those units had been published for the Midway Valley area until Taylor (1986) mapped the fluvial-terrace sequence along Yucca and Fortymile Washes, as well as in a small area in northernmost Midway Valley.

Table 3. Summary of diagnostic surface and soil characteristics of Quaternary map units in the Yucca Mountain area, southwestern Nevada.

[See Wesling and others (1992) for definitions of surface characteristics. Desert pavement, relative degree of interlocking of surface clasts, based on a qualitative estimate. Desert varnish: first number, average varnish cover (in percent, ±1σ); second number, abundance of varnished clasts (in percent) (Wesling and others, 1992). Rubification, abundance of rubified clasts (in percent) (Wesling and others, 1992). Depositional-bar relief, relative height of depositional bars from top of bar to trough of adjacent swale. Horizon sequence, sequence of soil horizons that is representative of each map unit: A, surface soil horizon characterized by accumulation of organic matter, typically as a zone of illuviation of clay, sesquioxides, silica, gypsum, carbonate, and (or) salts; B, subsurface soil horizon characterized by reddening, stronger development, and (or) accumulation of secondary illuvial materials (clay, sesquioxides, silica, gypsum, and salts); C, subsurface soil horizon that may appear similar or dissimilar to parent material and that includes unaltered material and material in various stages of weathering; K, subsurface soil horizon engulfed with carbonate to the extent that its morphology is determined by the carbonate. Master-horizon modifiers: j, used in conjunction with other modifiers to denote incipient development of that particular soil characteristic; k, carbonate accumulation; m, strong cementation; q, silica accumulation; t, clay accumulation; u, undifferentiated; v, vesicularity; w, color or structural B soil horizon. Structure: 1, weak; 2, moderate; 3, strong; f, fine grained; m, medium grained; pl, platy; sbk, subangular blocky; sg, single grained; vf, very fine grained. Clay films: 1, few; 2, common; 3, many; co, colloidal stains; mk, moderately thick; n, thin; pf, ped face. Maximum reddening, hue determined with Munsell Soil Color Charts (Munsell Color Co., Inc., 1988). $CaCO_3$ stage morphology from Gile and others (1966) and Birkeland (1984). Do., ditto; n.p., not present]

Unit (table 2)	Surface characteristics				Soil characteristics				
	Desert pavement	Desert varnish	Rubification	Depositional-bar relief	Horizon sequence	Structure	Clay films	Maximum reddening	Maximum $CaCO_3$ stage morphology
Qa7	None	1±2 12	4	High, unaltered---	Cu	sg	n.p..	10YR	n.p.
Qa6	None	0±0 0	0	do-------------	A-Ck	sg	n.p.	10YR	n.p.
Qa5	Weak to moderate--	1±1 28	33	Moderately high, slightly altered.	A-Bwk/ Btjk-Bk-Ck	1 vf-f sbk	n.p.-1 n co	10YR	I
Qa4	Moderate to strong--	62±27 97	87	Low---------------	Av-Btkq- Bkq-Ck	2–3 f-m sbk	3 n-mk pf	7.5YR	I–II
Qa3	Strong----------------	43±28 94	54	do-------------	Av-BA- Btkq-Kq/ Bkq-Ck	3 m sbk	3 n-mk pf	7.5YR	II+–III
Qa2	Strong----------------	80 (est.) 100 (est.)	100 (est.)	do-------------	Av-Btq- Btkq-Kq- Bkq-Ck	3 m sbk	3 mk pf	7.5–5YR	IV
Qa1	Locally strong-------	20±21 84	80	None--------------	Av-BA- Btkq-Kqm- Bkq-Ck	m-3 m pl	2 n pf	10–7.5YR	IV
QT0	Degraded-------------	Eroded-----------------------							

Taylor (1986) mapped six surficial deposits along Yucca and Fortymile Washes (fig. 2). Geologic units were differentiated and pedogenic soil profiles described to assess the influence of time and climate on soil development and to quantify the variation in past Quaternary climates on the basis of the degree of calcic-horizon development. Map units were assigned on the basis of an inferred correlation with the stratigraphic and numerical ages of Hoover and others (1981), Szabo and others (1981), and Swadley and Hoover (1983). Taylor demonstrated that the soil morphology and the progressive accumulation of secondary carbonate, clay, and silica correlate with age. Ca carbonate, Ca-Mg carbonate, and other carbonate species in soils were not distinguished. In this report, the term "carbonate" is used to refer to all pedogenic carbonate species, and the term "silica" to all pedogenic silica species, which Taylor (1986) showed to be predominately opal-CT. Taylor's work clearly demonstrated the usefulness of soils for stratigraphic correlation and for estimating the relative ages of surficial deposits in the Yucca Mountain area.

Wesling and others (1992) mapped the surficial geology of Midway Valley at a scale of 1:6,000, and S.C. Lundstrom (written commun., 1995) mapped the surficial geology of the eastern and southern Yucca Mountain area at a scale of 1:12,000. Those studies delineated eight informal alluvial geomorphic surfaces (QT0 through Qa7, table 2), as well as colluvial and eolian deposits, that represent the general Quaternary stratigraphic sequence now recognized in the Yucca Mountain area (col. 1, table 2).

Six major allostratigraphic units were delineated by Faulds and others (1994) and Peterson and others (1995) in Crater Flat, west of Yucca Mountain (figs. 1, 2). The stratigraphic framework thus established (col. 3, table 2) was applied for correlative purposes in studies of the surficial deposits and trench exposures along the Bare Mountain Fault on the west side of Crater Flat (see chap. 12).

Quaternary Deposits, Soils, and Geomorphic Surfaces

Quaternary deposits in the Yucca Mountain area include (1) alluvium that underlies alluvial-fan and fluvial-terrace surfaces and was deposited along active washes, (2) colluvial and debris-flow deposits present along the base and lower parts of the hillslopes bounding the valleys, (3) areas of mixed bedrock and thin colluvium in midslope and hilltop areas, and (4) eolian deposits. The informal allostratigraphic units exhibit surface properties that reflect variations among soil development, eolian deposition, clast weathering, desert-varnish accumulation, biologic activity, and progressive erosional instability that largely reflect their relative ages (table 3). The younger deposits (units Qa5–Qa7, table 2) exhibit relatively unaltered original-surface characteristics, including incipient to weak soil development, little to no desert-varnish accumulation or desert-pavement development, relatively unaltered bar-and-swale relief, and minimal eolian accumulations in the upper horizons of soil profiles. The older deposits (units Qa2–Qa4) have more strongly developed desert pavement, more continuously and darkly varnished clasts, greatly reduced bar-and-swale relief, strongly developed soils, and relatively thick accumulations of silt and fine sand in the upper parts of soil profiles. The oldest deposits (units QT0, Qa1) have degraded surface characteristics and soil profiles, reflecting erosional modification of geomorphic surfaces.

Soil profiles provide important supplementary information for reconstructing Quaternary history because the individual soil layers (or "horizons," the term used by soil specialists for both the soil layer and its component parts) represent time periods when the land surface was subjected to such soil-forming processes as physical weathering, infiltration and precipitation of secondary carbonate, and accumulation of eolian materials. Such factors as the composition of the parent material, climate, plant life, topographic relief, and time all affect soil development; the time factor is of principal interest with respect to the fault studies presented in this report. Given enough time, soils in the Yucca Mountain area developed with characteristics distinctive enough to locally form "marker" beds or horizons that can be mapped in trench exposures and have been used to help determine the timing and magnitude of Quaternary fault displacements. The chief value of well-developed soil horizons is that their secondary accumulation of mineral components can provide age data and be used as criteria for the relative dating of the host deposits. Although numerical age data are sparse, a well developed soil in the Yucca Mountain area is considered to represent a period of tens of thousands of years—evidence that, if that soil is subsequently displaced, can be used to date a faulting event.

The mapping of soil horizons is independent of the mapping of lithostratigraphic units in the same trench exposure. Soils form not only on undisturbed deposits, but also on erosional surfaces that may crosscut such deposits; thus, soils may be conformable or nonconformable horizons within a trench section. Furthermore, soils are formed within (or "on," as expressed by soil specialists) the host depositional sequence as physical and chemical processes alter the primary characteristics of that sequence. Subsequent accumulations of alluvial, colluvial, and eolian deposits can erode into or bury older soils and sedimentary sequences. Thus, soil profiles are typically described separately from stratigraphic sequences, as noted on many of the trench logs and tables presented in various chapters of this report.

Alluvial Deposits and Geomorphic Surfaces

Alluvial geomorphic surfaces are the dominant Quaternary landforms in the Yucca Mountain area (fig. 1). The materials associated with those surfaces include alluvium and minor eolian and debris-flow deposits. Sedimentologic properties of the various alluvial deposits are similar. In general, the fluvial deposits consist predominately of sandy gravel, with interbedded gravelly sand and sand. The fluvial facies include relatively coarse grained channel bars and intervening finer grained swales. The texture of materials in the bars and swales depends on their position within the landscape (proximal- or distal-fan region) and on sediment source. In the proximal-fan region, grain size is greater where coarser sediment is available for transport and where streamflow is concentrated; in the distal-fan region, grain size is smaller, although coarser grained facies are present locally. Gravel size ranges from pebble to boulder, and clasts generally are subangular to subrounded.

In test-pit and streamcut exposures of units Qa5 through Qa7 (table 2), the cross-sectional bar-and-swale characteristics are so well preserved that the facies changes between the bars and swales are readily distinguishable. The materials associated with bars include non-indurated, cobble-boulder gravel and finer grained sand and gravel; the materials associated with swales include a finer grained, silt-rich, sandy gravel and gravelly sand. The boulder-gravel deposits associated with the bars typically are about 0.5 m thick. Unweathered deposits are light gray (10YR 7/2 d; Munsell Color Co. Inc., 1992), poorly to moderately well sorted, well bedded to massive, and clast to matrix supported. Rodent burrows are ubiquitous in units Qa5 and Qa6, likely reflecting the ease of excavation. Unit Qa5 and younger deposits are relatively loose and do not hold a well-formed free face when excavated. In test-pit and streamcut exposures, buried soils are commonly observed in intervals less than 2 to 3 m thick. The buried soils may be older stratigraphic units, or they may represent a hiatus in the aggradational sequence of a single depositional unit. Where they represent a hiatus, the surface-soil characteristics reflect variations in the length of exposure.

Debris-flow deposits, observed locally in outcrops, test pits, and trenches, are matrix supported and range in textures from silt to cobbles; the gravel fraction composes approximately 15 to 30 volume percent of the deposit. The debris-flow deposits are massive and relatively hard.

Although the relative ages of the deposits, soils, and geomorphic surfaces around Yucca Mountain are well established on the basis of distinctive surface properties and soil-profile characteristics, as discussed above, only limited direct numerical-age control is available. Establishing a reliable temporal framework is difficult because of the uncertainties involved in dating complex geomorphic and pedogenic systems in an arid environment. The difficulties are further compounded by a general lack of suitable materials for dating and by variation in the ages of individual deposits not only from top to bottom but also laterally, owing to their time-transgressive nature. The two primary dating techniques used in the paleoseismic studies presented in the various chapters of this report are (1) U-Th-disequilibrium series (U series) analysis of carbonate- and silica-rich materials in soils and (2) thermoluminescence analysis of the silt-size fraction of eolian and fluvial deposits. These two techniques, which have been widely applied in recent years, are considered to provide the most reliable ages for investigating the Quaternary stratigraphy and structure of the Yucca Mountain area.

Earlier studies of surficial deposits (for example, Swadley and others, 1984; Rosholt and others, 1985) depended on dating by U-trend analysis, the results of which have since been considered to be highly unreliable (J.B. Paces, written commun., 1995). For the stratigraphic and fault studies presented in various chapters of this report, the only U-trend dates cited are those from trench T14 on the Bow Ridge Fault (fig. 2; see chap. 5; table 9) and from trench CF3 on the Windy Wash Fault (see chap. 9, table 27). In neither trench have such ages been used to date paleoearthquakes, but they are merely cited as previously published information.

We emphasize that most of the samples collected and analyzed for age determinations were obtained from trenches that were located mainly to expose fault relations, rather than specifically for optimum study of surficial sequences and depositional processes, thus hindering to some degree a more systematic approach to establishing a complete, age-constrained stratigraphic framework.

For the present study, the numerical ages of the various surficial deposits (units QT0 through Qa7, table 2) that compose the Quaternary sequence at Yucca Mountain are based primarily on samples collected from units Qa2 through Qa5 as defined and mapped in the Midway Valley and Fortymile Wash areas (fig. 2; Wesling and others, 1992; S.C. Lundstrom, written commun., 1995). The ages of units Qa2 through Qa5 as determined by U-series and thermoluminescence analyses are listed in table 4, and the data are plotted in figure 3, which shows probability-density functions (PDFs) for the ages of these mapped surficial deposits as determined by S.K. Pezzopane (written commun., 2000). Each PDF is constructed from the sum of normal-distribution functions (not shown) that represent the sample age and laboratory errors, normalized by the number of ages (N, above each PDF) from each stratigraphic unit (Qa2–Qa5 beneath each PDF). The normal-distribution function for each age is based on the mean and a 3σ error, which is spread about the mean out to ±3 times the 2σ (95-percent confidence) errors, as reported by J.B. Paces and S.A. Mahan (written commun., 1995). The relative scale for each PDF is expressed as relative probability (in percent) per thousand years. The median age (number beside bar) and the ±2σ (numbers at limits of shaded areas) age ranges for the units are derived from the cumulative distribution functions (not shown) summed from each PDF. A few obvious outlier data were eliminated, such that each shaded area represents the principal age distribution based on a subset number (*n*) of dates. The data show that for units Qa2, Qa4, and Qa5, a distinct clustering of dates is noticeable within relatively narrow segments of the age ranges (shaded areas on each PDF, fig. 3), which are interpreted to best represent the main periods of deposition and (or) soil development for those units. Ages outside these ranges (unshaded areas) could be caused by miscorrelation of the sampled deposits, or they may, in fact, represent valid extensions of the age boundaries, thus indicating that absolute temporal boundaries cannot be established between successive units. For unit Qa3, for example, at least two depositional episodes may be included within the whole unit.

On the basis of the data discussed above, the preferred ages of the dated surficial deposits are as follows: unit Qa2, 380+350/−110 ka (middle Pleistocene); unit Qa3, 86+40/−16 ka (older subunit) and 51+12/−17 ka (younger subunit) (middle? to late Pleistocene); unit Qa4, 27±10 ka (late Pleistocene); and unit Qa5, 7+10/−5 ka (latest Pleistocene to early Holocene). Evidence indicates that unit Qa1 is associated with a period of deposition as early as the Bishop ash (760 ka; Sarna-Wojcicki and others, 1993), and so the unit is dated at possibly early to middle Pleistocene. The underlying unit QT0 is assumed to be older than 760 ka, possibly as old as Pliocene. Units Qa6 and Qa7 are presumed to be younger than 7 ka; unit Qa6 is dated at middle to late Holocene, and unit Qa7 is the deposit presently accumulating along modern streamcourses.

Numerous samples were collected from the surficial deposits exposed in trenches for numerical-age determinations that can be used to estimate the timing of Quaternary depositional and deformational events along or near the 11 major faults (or fault systems) discussed in the various chapters of this report. Such numerical-age determinations are listed in the tables in each chapter. In some fault studies, the presence of basaltic ash in fault zones that correlate with an eruption of the nearby Lathrop Wells volcanic center (fig. 1), which is dated at 77±6 ka (Heizler and others, 1999), aided in reconstructing the timing of Quaternary deformation.

Table 4. Numerical ages of samples collected from Quaternary deposits (units Qa2–Qa5, table 2) in Midway Valley and Fortymile Wash in the Yucca Mountain area, southwestern Nevada.

[See figures 1 and 2 for locations. Samples: TL– (error limits, ±2σ), thermoluminescence analyses by S.A. Mahan; HD (error limits, ±2σ), U-series analyses by J.B. Paces]

Unit (table 2)	Sample	Material sampled	Age (ka)
Qa5	TL–08	Sand and silt	12±2
	TL–13, TL–14	Eolian sand	7±1, 8±1
	TL–41	Sandy lens	4±0.4
	TL–42	Gravelly alluvium	7±1
	TL–50	Bt soil horizon	26±2
	TL–51	do	4±3, 5±1
	TL–52	do	4±1
	TL–76	do	13±2
	TL–79	Silt and sand	7±1
	TL–80	do	6±0.5
	HD 2138	Clast rind	7±6, 9±1, 9±1
	HD 1637	Gravelly alluvium	7±5, 7±6
Qa4	TL–01	Av soil horizon	27±5
	TL–50	Bt soil horizon	26±2
	HD 2123	Clast rind in K soil horizon	21±3, 23±2, 25±6, 36±1
	HD 2124	do	27±2, 30±2, 31±3
Qa3	TL–48	Bt soil horizon	27±3
	TL–78	Silt and sand	55±7
	HD 972	Colluvium, platy K soil horizon	41±8
	HD 1375	Clast rind in K soil horizon	45±2, 49±3, 51±7, 53±2
	HD 1916	Ck soil horizon	27±3, 30±8, 74±3
	HD 2136	Clast rind in K soil horizon	49±3, 53±2, 60±3
	HD 2137	K soil horizon	75±1, 78±1, 85±5
	TL–47	Sand below K soil horizon	103±17
	HD 1740	2Btb soil horizon	90±7, 93±4, 101±21, 108±8
	HD 1741	K soil horizon	152±8, 169±5, 170±3
Qa2	TL–77	Silt and sand	104±44
	HD 2134	K soil horizon	411±63
	HD 2135	do	305±21, 347±16, 449±53, 567±147

General descriptions of the eight identified surficial deposits and associated soil profiles, as well as additional discussions of their assigned ages, are given below, in ascending order.

Unit QT0

Unit QT0 (table 2) consists of a single terrace remnant on the upthrown block of the Paintbrush Canyon Fault at the north end of Alice Ridge (fig. 2). The surface forms a pronounced topographic bench (elev 1,168 m) that is 25 m higher than unit Qa1 and 46 m above the active channel of Yucca Wash. Deposits associated with unit QT0 consist of lag gravel on a bedrock surface eroded into the 12.7-Ma Tiva Canyon Tuff (Sawyer and others, 1994). Clast types that include the rhyolites of Fortymile Wash are sufficiently abundant and distinct to indicate that the clasts are exotic to Alice Ridge. Because of its limited areal extent and the extensive postdepositional erosion of surficial materials, no detailed soil data were collected from the unit QT0 surface (table 3). An unusual characteristic of the deposit is that the cemented matrix commonly is more resistant to erosion than the clasts. The thickness of the unit is unknown but is probably only a few meters. The possibly Tertiary to early Quaternary age of unit QT0 is based not only on its stratigraphic position relative to unit Qa1 but also on its highly dissected and eroded surface and its rounded landform morphology.

Unit Qa1

Unit Qa1 (table 2) is preserved at the surface on the Yucca Wash alluvial fan north of Sever Wash in Midway Valley (fig. 2); the fan surface has been dissected by younger drainages and is preserved as slightly rounded interfluves. Unit Qa1 also is mapped on the west flank of Yucca Mountain and in northeastern Crater Flat. Locally, the desert pavement associated with the unit Qa1 surface is well developed, but in most areas it has been extensively degraded (table 3). Several characteristics, including freshly exposed rock surfaces on clasts, fragments of secondary carbonate and silica platelets, and surface or near-surface calcic horizons, collectively impart a light tonal quality to the unit as viewed in the field or on aerial photographs. Although darkly varnished clasts are present in some areas, surface clasts typically are not darkly varnished. No original depositional bar-and-swale morphology is preserved on the unit Qa1 surface, and larger clasts appear to be distributed randomly rather than concentrated in areas that define depositional bars. Angular unvarnished rock fragments are common on the surface, where larger varnished clasts have spalled, exposing fresh rock surfaces. Many clasts are fractured and strongly weathered. A buried soil was observed beneath unit Qa1 at 2.5-m-depth in one test pit, but no buried soils were exposed more than 3.3 m deep in other test pits.

The strongly developed Qa1 soil is more than 1.5 to 2.0 m thick and has a laminar petrocalcic horizon (Kqm) with $CaCO_3$ stage IV morphology at or near the surface (table 3). The petrocalcic horizon locally is overlain by as much as 30 cm of fine-grained eolian sand and silt. Soil development on the eolian deposits is characterized by brown to red (10–7.5YR) Bkq and Btkq horizons with a strong, medium-subangular blocky structure and continuous, moderately thick clay films. The soil developed in the overlying eolian sand and silt

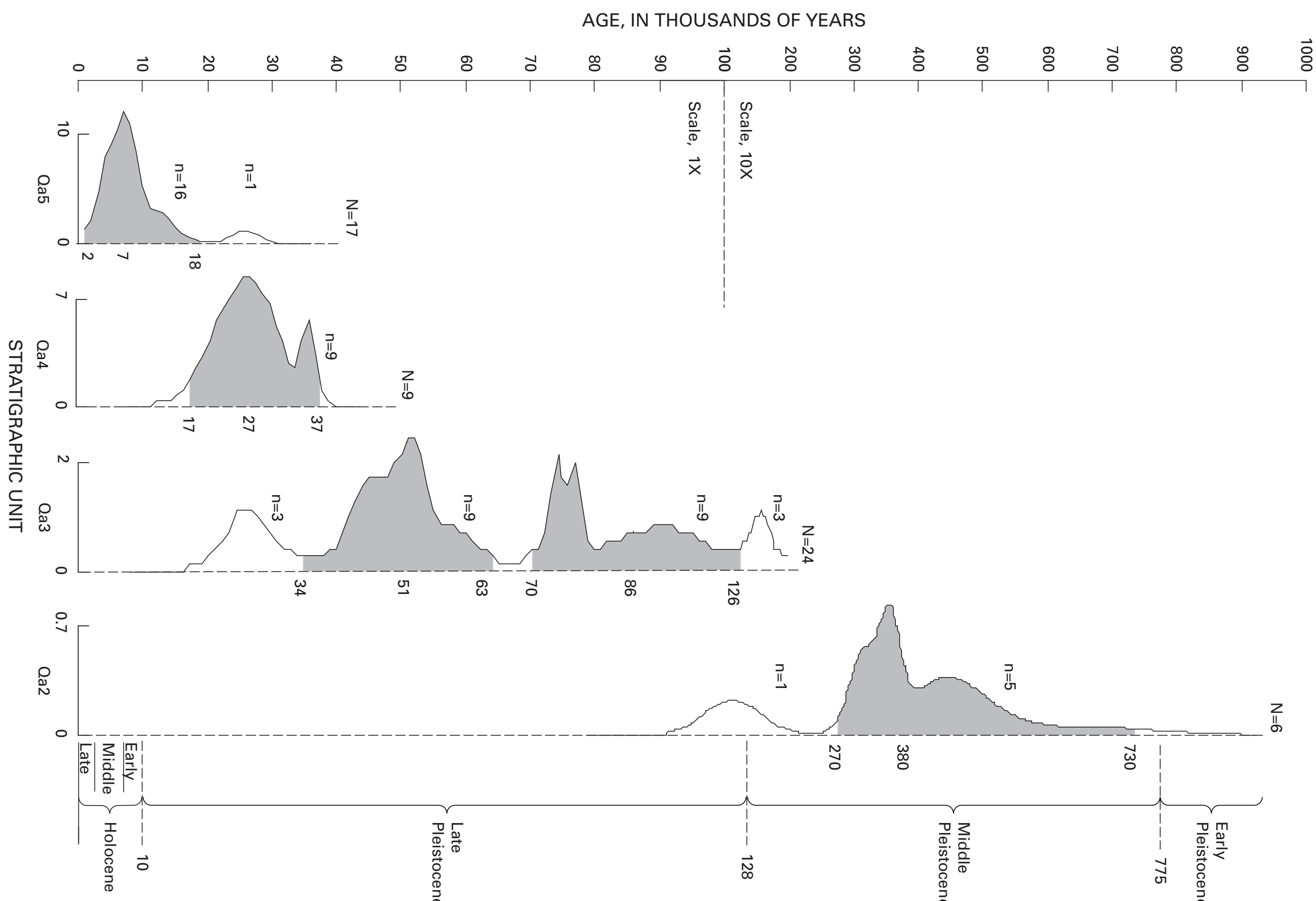

Figure 3. Schematic stratigraphic column showing age distribution (in percent) of mapped Quaternary deposits (units Qa2–Qa5) in Midway Valley and Fortymile Wash in the Yucca Mountain area, southwestern Nevada (figs. 1, 2). Marker dates: 775 ka, age of Matuyama-Brunhes chronozone boundary (Morrison, 1991); 128 ka, astronomical age of marine O-isotopic-substage 5e boundary (Imbrie and others, 1984); 10 ka, arbitrary age suggested for Pleistocene-Holocene boundary (Hopkins, 1975).

appears to be much younger than the underlying petrocalcic horizon formed in alluvial deposits.

Unit Qa1, of possibly early to middle Pleistocene age, which is correlated with unit QTa of Swadley and others (table 2) in Midway Valley, was considered by them to be overlain by alluvial deposits containing Bishop tephra (~760 ka; Sarna-Wojcicki and others, 1993). M.C. Reheis (oral commun., 1993) and Peterson and others (1995), however, reported Bishop tephra within alluvial deposits mapped earlier as unit QTa by Swadley and others (1984) in northeastern Crater Flat. Peterson and others (1995) correlated unit QTa with their Solitario geomorphic surface, which they dated at 430–730 ka on the basis of varnish cation-ratio ages and the age of the Bishop ash (760 ka in the present study). According to S.C. Lundstrom (written commun., 2001), ash deposits interpreted to be representative of the Bishop ash are also present in unit Qa1 deposits along Yucca Wash (fig. 2). Furthermore, the slightly rounded, eroded morphology of unit Qa1 surfaces, as well as the strongly developed soils, are similar features of deposits dated at early to middle Pleistocene elsewhere in Nevada and in California (Wells and others, 1990; Harden and others, 1991a, b; Slate, 1991; Reheis and others, 1992; McDonald and McFadden, 1994).

Unit Qa2

Unit Qa2 (table 2) is recognized at the surface primarily as thin elongate patches of alluvium in Midway Valley, where it is inset into unit Qa1. On color aerial photographs, unit Qa2 surfaces have a darker, redder hue than those of other units. The unit also has a well-developed desert pavement that contains darkly varnished clasts (table 3). Some clasts are split and fractured, and varnish has developed on some fractured surfaces of clasts. The original bar-and-swale morphology has been reduced to the height of the larger clasts above the surface. The upper part of the unit typically has a cap of eolian silt and fine sand, 30 to 50 cm thick. As observed in test pits, unit Qa2 ranges from 2.5 to more than 3.5 m in thickness.

The strongly developed Qa2 soil has a 40- to 70-cm-thick, reddened (7.5–5YR) argillic Btkq horizon and a zone of secondary carbonate and silica accumulation exhibiting $CaCO_3$ stage II–III+ morphology (table 3). The upper column (Av and Bkq horizons) of the Qa2 soil is formed in the eolian deposits that accumulated on the surface (table 3). The upper part of the Bkq soil horizon lacks significant carbonate but contains a laminar silica-cemented zone that is reddish brown to yellowish red (5YR 5/4–6 d). Therefore, the morphology of the upper part of the soil is controlled by silica accumulation, whereas the morphology of the lower part of the soil is controlled by both secondary carbonate and silica accumulation, giving the Qa2 soil an overall appearance of $CaCO_3$ stage IV morphology.

The few dated samples from unit Qa2 (fig. 3) indicate a middle Pleistocene age, which is supported by its stratigraphic position, as well as by the degree of soil development within it.

Unit Qa3

Unit Qa3 (table 2), which is represented by large remnant alluvial-fan surfaces and fluvial terraces, is one of the dominant lithologic units in the Yucca Mountain area, where it underlies the main Fortymile Wash terrace. A well-developed desert pavement containing darkly varnished clasts characterizes the unit Qa3 surface, which has a dark-brown or black tone on color aerial photographs (table 3). Larger clasts, some more than 30 cm in diameter, are distributed on the surface in diffuse, poorly defined bars. The original depositional bar-and-swale morphology has been reduced to the height of individual clasts above the surface. Unit Qa3 averages 2 to 2.5 m in thickness and locally is more than 3.3 m thick in test pits and along the Fortymile Wash terraces.

The strongly developed Qa3 soil has a 20- to 75-cm-thick argillic (Bt and Bkq) horizon overlying a 100- to 130-cm-thick zone of secondary carbonate and silica accumulation (table 3). Clay films, reddening (7.5YR), and strong blocky structure are characteristic of the argillic horizon, which also commonly contains secondary carbonate and silica accumulations. A Bkq or weakly developed Kq soil horizon with $CaCO_3$ stage II–III morphology typically underlies the Bkq soil horizon.

Unit Qa3 is dated at middle(?) to late Pleistocene on the basis of numerical-age determinations (fig. 3), as well as on stratigraphic relations and lithologic and soil characteristics. As discussed above, the unit may be represented by more than one depositional episode.

Unit Qa4

Unit Qa4 (table 2) consists of small, inset fluvial-terrace and alluvial-fan remnants on the east side of Yucca Mountain and of thin alluvial deposits overlying older basin deposits in Crater Flat. The desert pavement of the unit Qa4 surface ranges in appearance from loosely to tightly interlocking and is noticeably less well developed than pavements formed on the older fluvial surfaces. Although desert varnish is discernible on surface clasts of the unit Qa4 pavement, varnish is much less common than on surface clasts of older units (table 3). Indistinct depositional bars are preserved as diffuse accumulations of larger clasts; bar-and-swale relief on unit Qa4 mostly has been reduced to clast height above the surface. Unit thickness averages about 1 m and does not exceed 2 m where observed in test-pit and trench exposures.

The strongly developed Qa4 soil is characterized by a reddened (7.5YR) argillic horizon and by secondary carbonate and silica accumulations (table 3). The upper part of the soil exhibits silica accumulation, $CaCO_3$ stage I–II morphology, and a strongly developed Bkq horizon with a sandy or silty clay-loam texture. Continuous, thin to moderately thick clay films coat ped faces of the Bkq soil horizon, which is overlain by an Av soil horizon.

Unit Qa4 is dated at late Pleistocene on the basis of U-series and thermoluminescence analyses (fig. 3; table 4), supported by similarities in soil-morphologic characteristics with chronosequences in other areas that were deposited about 80–15 ka (table 2).

Unit Qa5

Unit Qa5 (table 2) covers large areas of alluvial fans and occurs as inset terraces along drainages. The desert pavement of the unit Qa5 surface is loosely packed and poorly formed, and surface clasts have minor accumulations of rock varnish (table 3). Unit Qa5 surfaces display well-developed bar-and-swale morphology. The amount of bar-and-swale relief is related to landscape position and sediment source. The coarsest grained bars lie in proximal-fan region, whereas smaller, lower, partly buried bars lie in the distal-fan region, where the intervening swales are partly filled by fine-grained eolian silt and sand. Surface clasts are relatively unweathered. Unit Qa5 averages 1 m in thickness, and is as much as 2.5 m thick in test-pit and trench exposures.

Weakly developed soils are formed on unit Qa5 (table 3). Soil development is stronger in the swales, where a silt-rich zone occurs in the upper 30 to 40 cm of the unit; soils are more weakly developed on bars. The unit Qa5 soil typically has a Bwk or incipient Btjk horizon with 10YR hues, weak subangular blocky structure, and colloidal stains on grains. Carbonate is disseminated in the matrix, and below about 30-cm depth in the Bk soil horizon the bottoms of clasts have powdery coats of carbonate with $CaCO_3$ stage I morphology. Where unit Qa5 is sufficiently thick, the carbonate content decreases below the Bk soil horizon to form a transitional horizon (BC or CB) or a Ck soil horizon (see table 3 for explanation). Where the unit Qa5 surface is relatively thin and underlain by a buried soil, the Bk horizon persists to the base of the unit.

Unit Qa5 is dated at latest Pleistocene to early Holocene on the basis of numerical-age determinations on samples from the Yucca Mountain area (fig. 3) and correlations to regional soil profiles (table 2). In Crater Flat, for example, Peterson and others (1995) reported that radiocarbon dating of rock varnish yielded a minimum age of 6–11 ka for the Little Cones unit, which has a soil profile similar to that of unit Qa5. The characteristically weak soil development exhibited by correlative units was interpreted by Dohrenwend and others (1991) as indicative of a Holocene age.

Unit Qa6

Unit Qa6 (table 2) is present along the active washes as low flood plains less than 1 m above the active channels, and as vegetated bars. No desert pavement has developed (table 3), and surface clasts are unvarnished and unweathered. Relief on the unit Qa6 surface is primarily the result of preservation of original bar-and-swale morphology. Locally, an eolian cap, as much as 5 to 10 cm thick, buries all but the largest surface clasts. Natural outcrops and manmade exposures indicate that the total thickness of unit Qa6 does not exceed 2 m.

Unit Qa6 soils lack the prominent eolian cap common to the older surfaces (Av horizon), and soil development is limited to minimal oxidation of the deposit and sparse secondary carbonate accumulation (table 3). Carbonate is more concentrated toward the uppermost 10 cm of the deposit but typically is widely disseminated in the matrix. Clasts in the upper 30 cm contain little visible carbonate yet effervesce when HCl is applied. Carbonate content ranges from isolated patches on the undersides of clasts to relatively continuous, thin coatings. Evidence that many of the clasts within unit Qa6 have been reworked from older deposits includes randomly oriented carbonate coatings on clasts and percussion marks where the coatings have been chipped from the clasts.

Unit Qa6 is assigned a middle to late Holocene age because of its very weak to weak soil development and its inset relation to unit Qa5. No color or structural B soil horizon is evident, and morphology ranges from incipient to $CaCO_3$ stage I. As listed in table 2, several middle to upper Holocene alluvial deposits are recognized in the region (Wells and others, 1990; Bull, 1991; Harden and others, 1991a; Slate, 1991).

Unit Qa7

Unit Qa7 (table 2) consists of deposits along active channels and the adjacent flood plains. No desert pavement has formed on its surface (table 3). No desert varnish has developed on clasts, except where it is apparently inherited. Thick, dark desert varnish is present in small protected areas (small fractures and exposed voids) on some surface and subsurface clasts; however, that varnish is too well developed to be actively accreting in modern channels and apparently has been reworked from older surfaces. Clasts are unweathered, and the original depositional bar-and-swale relief is unaltered. The total exposed thickness of unit Qa7 does not exceed 2 m.

No inplace pedogenic alterations were observed for unit Qa7 deposits (table 3). The overall color is pale brown to brown (10YR 5–6/3 d). The matrix contains reworked, disseminated carbonate. Reworking of older surficial materials is indicated by numerous clasts with thick secondary carbonate accumulations; such clasts appear to be distributed randomly throughout unit Qa7. The coatings, originally formed on the bottoms of the clasts, have no preferred orientation in the reworked deposits. Although carbonate is generally not apparent on the undersides of clasts, noticeable effervescence occurs when HCl is applied. This unit includes modern deposits in channels (unit Qa7) and on hillslopes (unit Qc7).

Colluvial Deposits

Colluvial deposits are undifferentiated as surficial map units because of their limited areal extent and the limited exposure of all but the youngest materials. However, colluvial sequences are exposed in fault trenches around Yucca Mountain and in test pits at the prospective site of surface facilities on the east side of Exile Hill (such as units Qc2, Qc3; see chap. 4; fig. 5). The colluvial stratigraphy of Midway Valley, as described below, is based primarily on test-pit and trench exposures.

Middle Pleistocene to Holocene Undifferentiated Colluvium (Unit Qu)

Unit Qu is mapped as colluvial and debris-flow deposits mantling hillslopes and locally includes areas mantled by eolian and reworked eolian deposits; patches of darkly varnished colluvial boulders are commonly on upper hillslopes (Whitney and Harrington, 1993). The colluvial deposits generally consist of gravelly-silty sand and silty fine to medium gravel with pebble to small cobble clasts. Colors are very pale brown (10YR 7/4 d) to reddish yellow (7.5YR 6/6), with white (10YR 8/1 d) for the older carbonate-cemented units. The colluvial and debris-flow deposits are poorly sorted and very crudely bedded to massive; they are predominantly matrix and locally clast supported and consist of as much as 90 percent gravel composed of angular to subangular pebbles with lesser cobbles, as much as 20 cm in diameter, and small boulders, as much as 30 cm in diameter. Individual colluvial deposits are generally less than 2 to 3 m thick, on the basis of test-pit and trench exposures.

The younger colluvial deposits, possibly equivalent to unit Qa5 (table 2), have thin, weakly developed soils, with an AB horizon over a weakly developed Bwk horizon. Colluvial deposits of probable unit Qa4 age display well-developed Bkq textural B soil horizons, 40 to 50 cm thick. Deposits possibly equivalent to units Qa2 and Qa3 have multiple superimposed soils consisting of Bkq and Btjkq horizons with $CaCO_3$ stage II morphology. The oldest exposed colluvial deposits have strongly developed Kqm soil horizons. The colluvial boulder deposits are dated at mid-Quaternary to late Quaternary (Whitney and Harrington, 1993).

Most of the hillslope areas mapped as undifferentiated colluvium have the same surface characteristics as units Qa5 and Qa6. Colluvial deposits with surface characteristics similar to those of unit Qa4 are common near the toe of the hillslope.

Eolian Deposits

Two types of eolian deposits were observed in the Yucca Mountain area: (1) reworked eolian materials within sand ramps surrounding Busted Butte and along the southeastern margin of Midway Valley, and (2) thin accumulations of silt and fine sand in the A and B horizons of most surface soils and relict accumulations within some buried soils.

Middle Pleistocene to Holocene Eolian-Colluvial Deposits (Unit Qeu)

Sand ramps at Busted Butte and in southeastern Midway Valley (fig. 2) consist of a stacked eolian-colluvial sequence composed of pebbly, silty, fine- to medium-grained sand interbedded with sandy pebble to cobble gravel. Minor sandy-pebble-gravel alluvial deposits are present locally. The sand-ramp deposits range in color from very pale brown to light gray (10YR 7/2–4 d), are poorly to moderately well sorted, and are moderately well bedded to massive. Unit Qeu is predominantly matrix supported, although the alluvial gravel and parts of some colluvial deposits locally are clast supported. Gravel clasts are angular to subangular and commonly less than 5 cm in diameter, some as much as 50 cm in diameter. The sand-ramp deposits do not exceed 15 m in thickness.

A weakly to moderately interlocking desert pavement covers most of the unit Qeu surface. Soil development in the near-surface deposits consists of a well-developed reddish-yellow (7.5YR 6/6 d) Bkq horizon with a sandy clay loam texture that appears to be similar to the unit Qa4 soil. Typically, one or more buried soils are within the sand-ramp deposits in Midway Valley. The buried soil observed within trench MWV–T4 (fig. 2) has a Kq horizon with $CaCO_3$ stage IV morphology. Additionally, multiple buried soils have been observed within the Busted Butte sand-ramp deposits south of Midway Valley (figs. 1, 2; Whitney and others, 1985; Whitney and Muhs, 1991; Menges and others, 1994).

The presence of Bishop tephra in the lower sand-ramp deposits at Busted Butte (Whitney and others, 1985; Menges and others, 1994) and in other localities near Yucca Mountain (Hoover, 1989) indicates that those landforms began forming before about 760 ka. At Busted Butte, some of the buried soils have been (U series) dated at middle to late Pleistocene (Menges and others, 1994). Multiple buried soils above the Bishop tephra indicate that accumulation of the sand ramps is episodic and punctuated by periods of surface stabilization and soil formation. Thermoluminescence ages of 73±9 and 38±6 ka on two successive units in the uppermost 3 m of the deposits exposed in trench MWV–T4 (fig. 2) in southern Midway Valley (samples TL–03, TL–04, table 9; see chap. 5) may date two of the more recent depositional episodes, and another thermoluminescence age of 6±1 ka (sample TL–05, table 9) on the A soil horizon indicates continuing eolian deposition during the Holocene.

Eolian Accumulations on Geomorphic Surfaces

A few to several tens of centimeters of eolian silt and fine sand have accumulated on most alluvial geomorphic surfaces and been incorporated into the soil profiles formed on those surfaces. These eolian deposits are not mapped separately because of their broad areal distribution and relative thinness. Models of desert pavement and soil formation recognize the importance of eolian materials as a source for the fine-earth fraction, carbonate, and soluble salts that occur within otherwise-clean sandy-gravel deposits in arid regions (Birkeland, 1984; McFadden and Weldon, 1987; McFadden and others, 1987; McDonald and McFadden, 1994).

Over time, surface weathering, soil formation, and eolian deposition result in incremental modifications to geomorphic surfaces, including reduction of the original surface topographic (bar and swale) relief, formation of Av soil horizons, desert-pavement development, desert-varnish accumulations on surface clasts, and weathering of surface clasts. In Midway Valley, these modifications have produced a distinctive surface morphology for a given unit that has been used as a basis for mapping alluvial geomorphic surfaces, whereby older surfaces generally have a more subdued surface topography, stronger desert-pavement development, darker and thicker desert varnish on surface clasts, stronger soil development, and thicker eolian deposits. Eolian additions to units Qa6 and Qa7 (table 2) are minimal, whereas eolian materials plug the upper part of unit Qa5 deposits and partly fill paleoswales to form a muted bar-and-swale topography. Unit Qa2 through Qa4 surfaces are plugged with eolian deposits that form a continuous surface sheet and result in a nearly smooth topography. The original eolian mantle on unit Qa1 has been stripped and replaced by a younger eolian mantle.

Summary

The differentiation and characterization of surficial deposits provide a stratigraphic framework that can be used as a common reference for interpreting Quaternary deformation across the Yucca Mountain area. The relative- and numerical-age relations among the various deposits and their correlative units in trench exposures are especially important for determining the timing and magnitude of past surface-rupturing paleoearthquakes, fault-slip rates, and recurrence intervals—data that are essential for evaluating the potential seismic hazards at Yucca Mountain.